Paris, 10 Mai 2022

Le carbone organique des sols agricoles : vers un suivi spatialisé satellitaire

Emmanuelle Vaudour

UMR ECOSYS, AgroParisTech

Actions en cours et prévues en lien avec le CES Théia CartoSols

« Développements sur la télédétection du Carbone des sols »

Emmanuelle Vaudour (ECOSYS), Diego Urbina-Salazar (ECOSYS, Infosol), Dominique Arrouays, Anne Richer-de-Forges (Infosol), Nicolas Baghdadi (TETIS), Youssef Fouad, Didier Michot (SAS), Nicolas Delbart (LIED), Florent Levavasseur (ECOSYS), Liliane Bel (MIA), Eric Ceschia (CESBIO), Cécile Gomez (LISAH), Philippe Lagacherie (LISAH)

UMR 1402 INRA/AgroParisTech « ECOSYS », Université Paris-Saclay
Pôle sol, Bât. EGER, Avenue Lucien Brétignières – F-78850 Thiverval-Grignon

Le CES Theia “Cartographie Numérique des sols”

Theia
Pôle Thématique
Surfaces Continentales

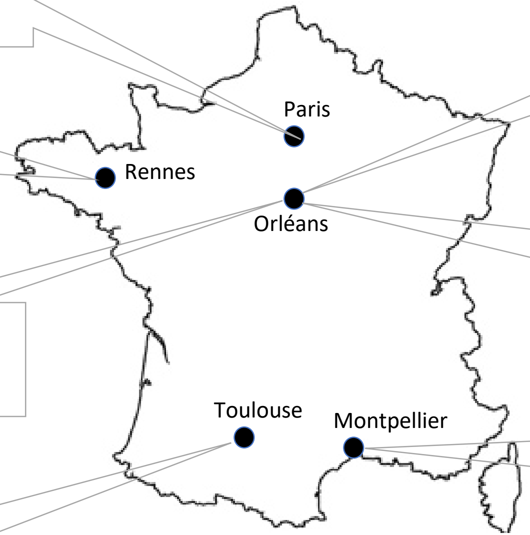
UMR ECOSYS
J.M. Gilliot, E. Vaudour

AgroParisTech

UMR SAS
Y. Fouad, B. Lemercier, D. Michot, C. Walter

BRGM
G. Martelet

ONERA
X. Briottet



UR SOLS
H. Bourennane, J. Daroussin

INRAE

US INFOSOL
D. Arrouays, M. Martin, A. Richer-de-Forges, N. Saby

INRAE

UMR LISAH
C. Gomez, P. Lagacherie

INRAE IRD

Digital Soil Mapping – The THEIA network

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

Travaux réalisés dans le cadre de financements

- TOSCA *CES-theia CNS*
- TOSCA *PLEIADES-CO*
- TOSCA *POLYPHEME*
- PNTS *EUSOP*
- ANR *ATCHA*
- *ANR RUEdesSOLS*

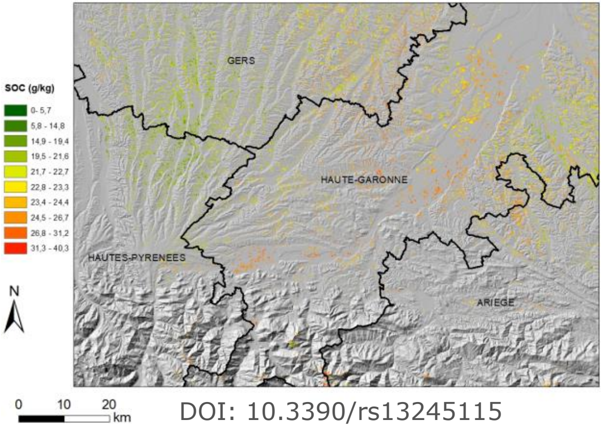
Objectifs

- Fédérer les efforts de recherche sur les verrous méthodologiques à lever (incubateur)
- Elaborer les produits *GlobalSoilMap* sur le territoire national et les territoires régionaux
- Organiser le transfert de compétence vers de nouveaux acteurs

POLYPHEME

Financement TOSCA du CNES

Suivi spatialisé des pratiques d'amendement organique et du carbone Organique des sols agricoles au moyen des séries POLYPhasées sEntinel Multispectrales Et radar



DOI: 10.3390/rs13245115

De janvier 2020 à décembre 2022

Partenaires :INRAE (ECOSYS, MIA-Paris, Infosol, CESBIO, SAS), PRODIG

Axe 1 : modèles spectraux de prédiction des teneurs en Corg via S2

Axe 2 : modèles spectraux raffinés via S1 et S2 et modèles mixtes stats

Axe 3 : suivi des pratiques (cultures ; cultures intermédiaires ; épandages de MO) par télédétection et influence sur prédiction Corg

Axe 4 : influence de l'occupation du sol ancienne – séries rétrospectives

STEROPES 2021-2024 (EJP SOIL - H2020)

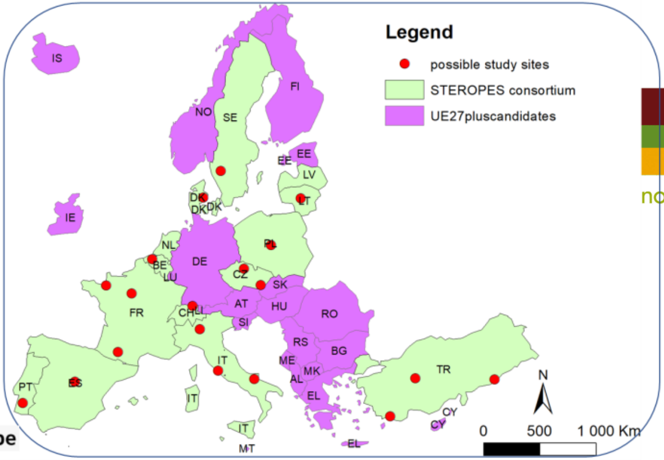
https://ejpsoil.eu/soil-research/steropes/

STEROPES

Stimulating novel Technologies from Earth Remote Observation to Predict European Soil carbon

Axes 1 – 2 (et 3 partiellement) de POLYPHEME, 14 pays

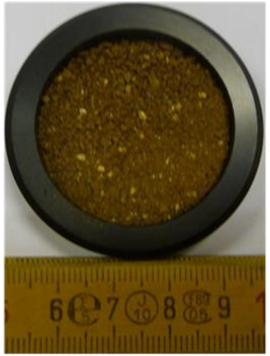
- débuté en février 2021



Overall background : from lab, field to image reflectance spectra

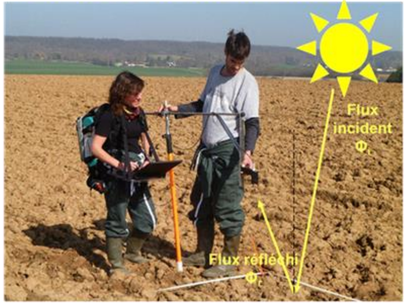
soil surface condition

soil sample in the lab



lab chemical analysis

field spectral measurements

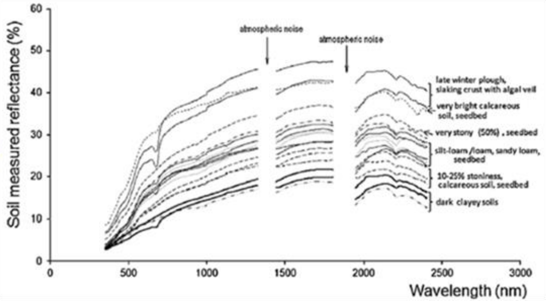


©UMR EGC-Equipe Sol, cliché E. Vaudour, mars 2012

lab spectral measurements

doi:10.3390/s18041157

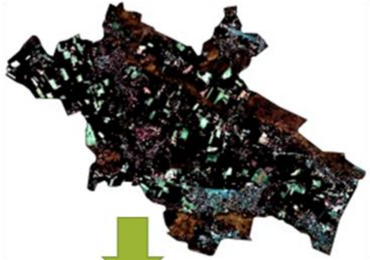
Barthès et al., 2008
Cécillon et al., 2009
Vaudour et al., 2018
Barthès and Chotte, 2020



doi:10.1016/j.jag.2013.07.003

Vaudour et al., 2014a
Vaudour et al., 2016
Dodin et al., 2021

Image of bare soils



Gomez et al., 2012, 2019, 2022
Vaudour et al., 2013, 2014a, b, 2016, 2019a,b, 2021
Gilliot et al., 2017
Urbina-Salazar et al., 2021

image reflectance spectra

field reflectance spectra

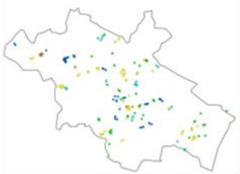
lab reflectance spectra

Gomez et al., 2017
Aïchi et al., 2021

spectral models
Property = f (R)

spatial models
Property = f (x, y)

Loiseau et al., 2019



sample locations

Zaouche et al., 2017
Mulder et al., 2016
Chen et al., 2019

Plan

1. Réflectance du sol en lien avec le carbone - jeux de données

2. Modèles spectraux de Corg issus d'images satellitaires

3. Caractérisation spectrale d'amendements organiques

Main properties influencing bare soil reflectance

VAUDOUR E., GIRARD MC., 2010. *Pédologie*, chapitre 23. In Girard MC & Girard CM, Traitement des images de télédétection, Dunod, Paris

©E. Vaudour – March 2012

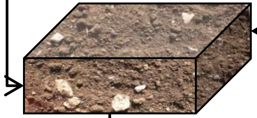
Soil surface condition « composition and organization of soil surface at a given time» - R. ESCADAFAL, 1989

static properties

SOC
$CaCO_3$
Fe
clay
coarse fragments

dynamic properties

roughness - slaking
soil moisture
green vegetation
dry residues
(coarse fragments)



soil reflectance

International Journal of Applied Earth Observation and Geoinformation 28 (2014) 43–59

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Mapping tillage operations over a peri-urban region using combined SPOT4 and ASAR/ENVISAT images

E. Vaudour[a,b,*], N. Baghdadi[c], J.M. Gilliot[a,b]

[a] AgroParisTech, UMR 1091 INRA/AgroParisTech "Environnement et Grandes Cultures", Equipe Sol, avenue Lucien Brétignières, F-78850 Thiverval-Grignon, France
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International Journal of Applied Earth Observation and Geoinformation 26 (2014) 217–234

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

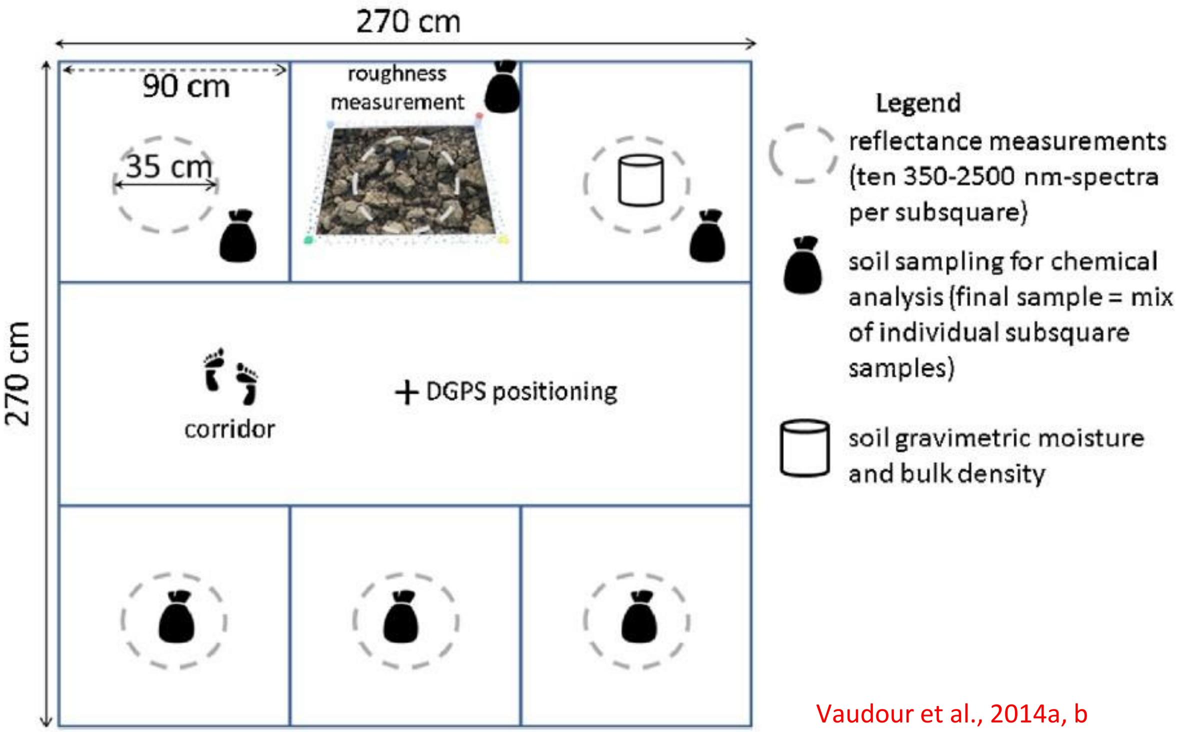
journal homepage: www.elsevier.com/locate/jag

Uncertainty of soil reflectance retrieval from SPOT and RapidEye multispectral satellite images using a per-pixel bootstrapped empirical line atmospheric correction over an agricultural region

E. Vaudour[a,b,*], J.M. Gilliot[a,b], L. Bel[c,d], L. Bréchet[b,a], J. Hamiache[c,d], D. Hadjar[b,a], Y. Lemonnier[b,a]

[a] AgroParisTech, UMR 1091 INRA/AgroParisTech «Environnement et Grandes Cultures», Equipe Sol, avenue Lucien Brétignières F-78850 Thiverval-Grignon, France
[b] INRA, UMR 1091 INRA/AgroParisTech «Environnement et Grandes Cultures», Equipe Sol, avenue Lucien Brétignières F-78850 Thiverval-Grignon, France
[c] AgroParisTech, UMR 518 MIA, 16, rue Claude Bernard, F-75231 Paris cedex 05, France
[d] INRA, UMR 518 MIA, 16, rue Claude Bernard, F-75231 Paris cedex 05, France

Field reflectance measurements



Vaudour et al., 2014a, b


Computers and Electronics in Agriculture 134 (2017) 63–78

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

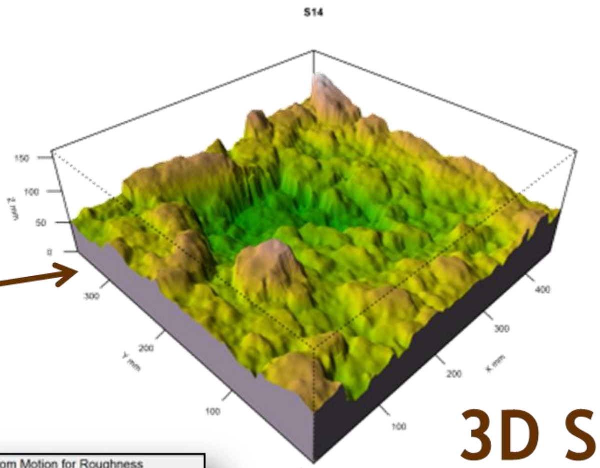
Soil surface roughness measurement: A new fully automatic photogrammetric approach applied to agricultural bare fields

J.M. Gilliot *, E. Vaudour, J. Michelin

UMR ECOSYS, INRA, AgroParisTech, Université Paris-Saclay, 78850 Thiverval-Grignon, France

Soil surface roughness estimation : a 3D photogrammetric approach based on Visual SFM

Gilliot et al., 2017



3D SSR model


International Journal of Applied Earth Observations and Geoinformation 96 (2021) 102277

Contents lists available at ScienceDirect

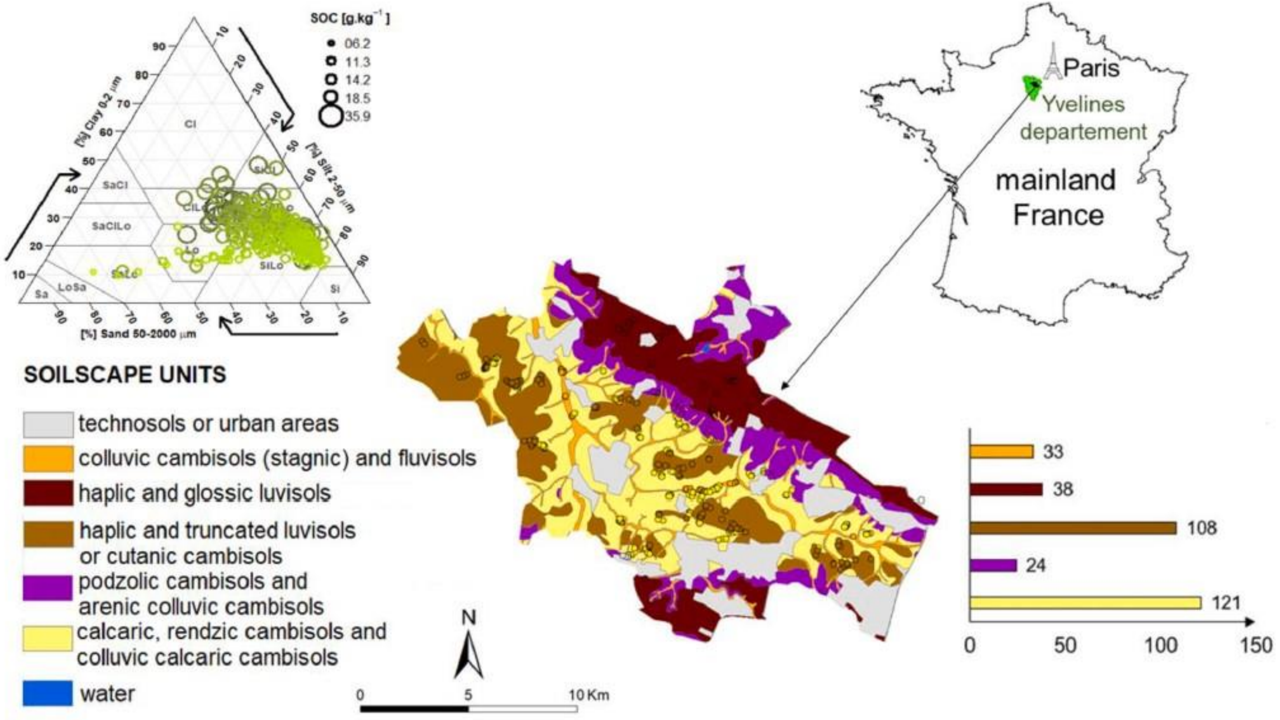
International Journal of Applied Earth Observations and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Temporal mosaicking approaches of Sentinel-2 images for extending topsoil organic carbon content mapping in croplands

Emmanuelle Vaudour[a,*], Cécile Gomez[b,c], Philippe Lagacherie[b], Thomas Loiseau[d], Nicolas Baghdadi[e], Diego Urbina-Salazar[a], Benjamin Loubet[a], Dominique Arrouays[d]

Dataset “Plaine de Versailles”



Vaudour et al., 2021

International Journal of Applied Earth Observation and Geoinformation 49 (2016) 24–38

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

cal-val approach

Regional prediction of soil organic carbon content over temperate croplands using visible near-infrared airborne hyperspectral imagery and synchronous field spectra

E. Vaudour[a,*], J.M. Gilliot[a], L. Bel[b], J. Lefevre[c], K. Chehdi[c]

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[b] UMR MIA-Paris, AgroParisTech, INRA, Université Paris-Saclay, 75005 Paris, France
[c] Université de Rennes 1/IETR UMR CNRS 6164, ENSSAT/TSI2M, 6 rue de Kérampont, B.P. 80518, F-22305 Lannion cedex, France

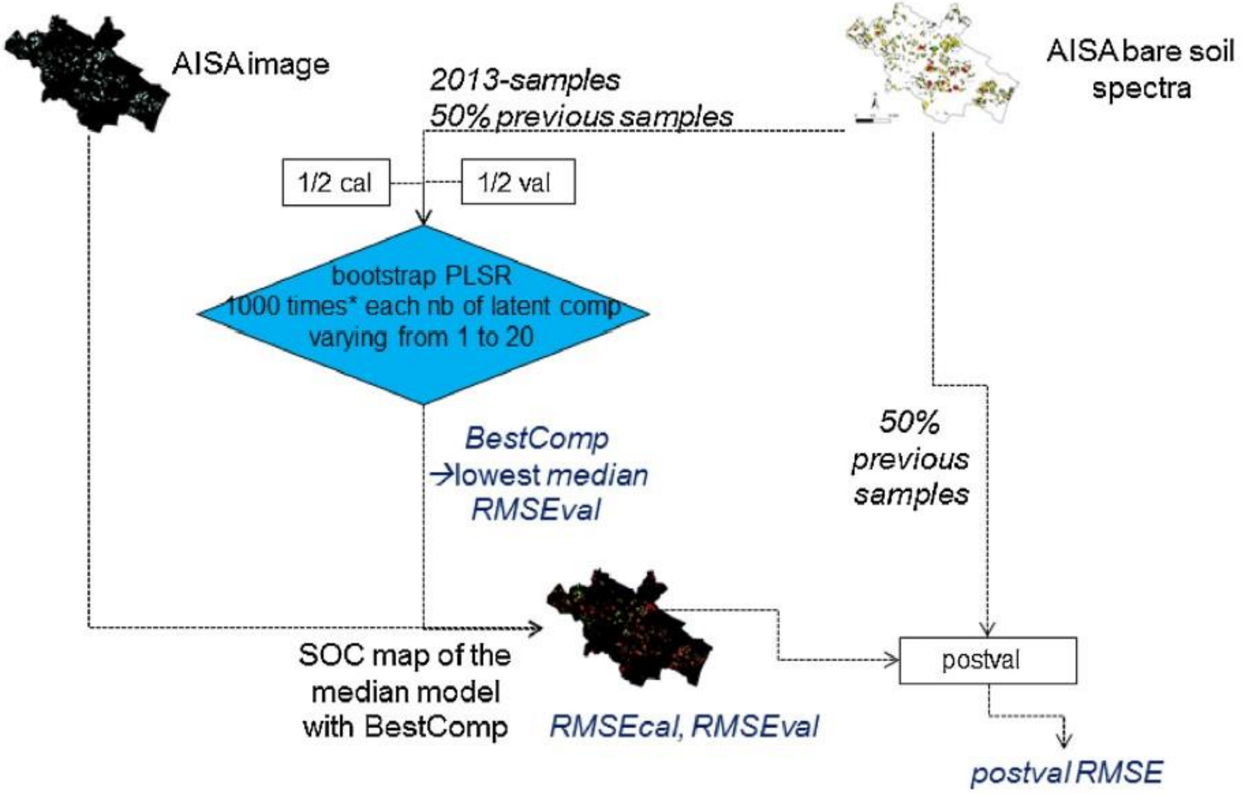


Fig. 3. Bootstrapped-PLSR SOC modeling approach (adapted from Vaudour et al., 2013).

Vaudour et al., 2016

International Journal of Applied Earth Observation and Geoinformation 49 (2016) 24–38

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Influence of soil surface condition

Regional prediction of soil organic carbon content over temperate croplands using visible near-infrared airborne hyperspectral ima and synchronous field spectra

E. Vaudour[a,*], J.M. Gilliot[a], L. Bel[b], J. Lefevre[c], K. Chehdi[c]

[a] UMR ECOSYS, AgroParisTech, INRA, Université Paris-Saclay, 78850 Thiverval-Grignon, France
[b] UMR MIA-Paris, AgroParisTech, INRA, Université Paris-Saclay, 75005 Paris, France
[c] Université de Rennes 1/IETR UMR CNRS 6164, ENSSAT/TSI2M, 6 rue de Kérampont, B.P. 80518, F-22305 Lannion cedex, France

Residual prediction deviation

$$RPD = \frac{\sigma_y}{RMSE}$$

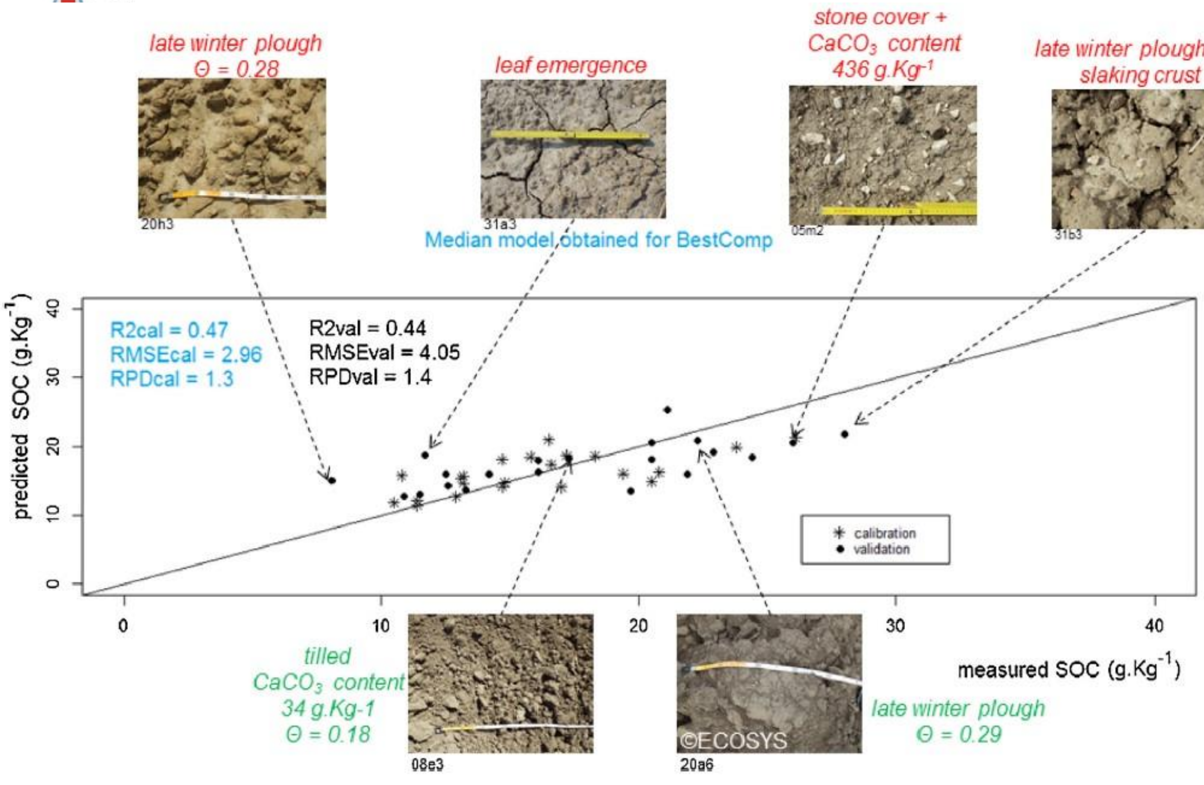


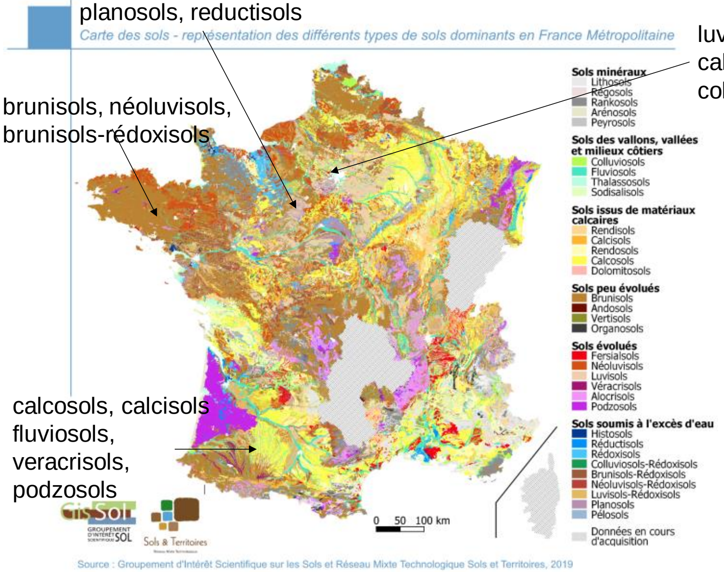
Fig. 7. Influence of soil surface condition.

Vaudour et al., 2016

Base de données sols projet POLYPHEME

- Types de sols très diversifiés sur des régions vastes et représentatives des principaux agroécosystèmes de grandes cultures tempérés (Bassin Parisien, Centre, Sud-Ouest, Bretagne)

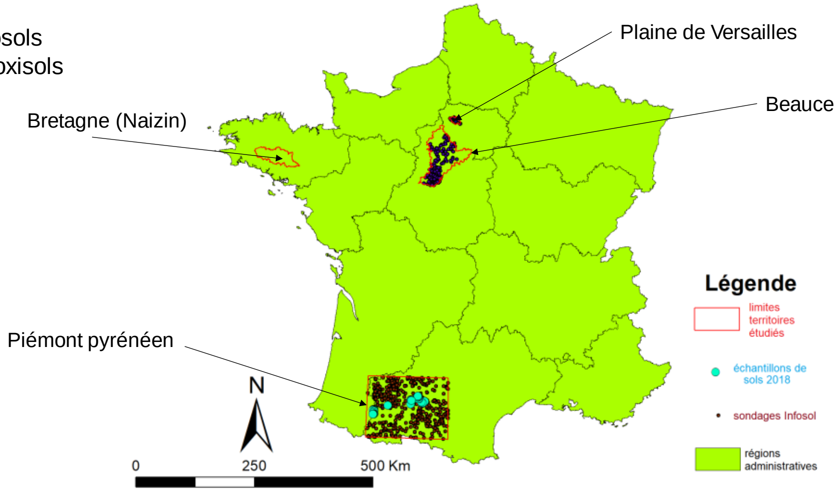
luvisols, rendosols, planosols, reductisols



luvisols, calcosols, rendosols colluviosols rédoxisols

brunisols, néoluvisols, brunisols-rédoxisols

calcosols, calcisols fluviosols, veracrisols, podzosols



Plaine de Versailles

Beauce

Bretagne (Naizin)

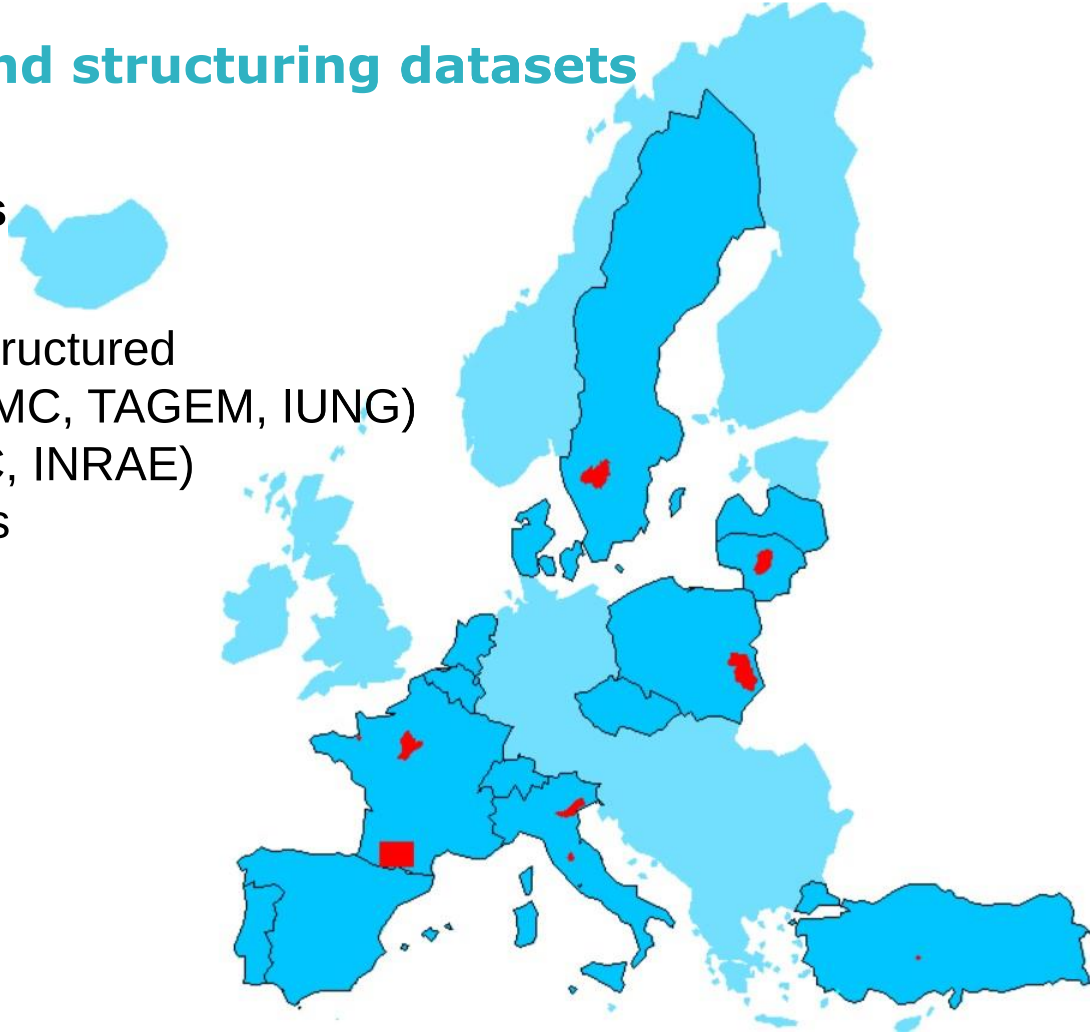
Piémont pyrénéen

URBINA-SALAZAR, thèse en cours
ZHAYANI, thèse en cours
DODIN, thèse en cours

STEROPES WP1
Task 1: Collecting, selecting and structuring datasets

- **Summary for regional databases**

9 regional databases collected and structured
3 sampling surveys carried out (LAMMC, TAGEM, IUNG)
2 sampling surveys planned (LAMMC, INRAE)
5 databases processed or in progress



EJP SOIL
STEROPES

Expected error according to scale

International Journal of Applied Earth Observation and Geoinformation 49 (2016) 24–38

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journal homepage: www.elsevier.com/locate/jag

Regional prediction of soil organic carbon content over temperate croplands using visible near-infrared airborne hyperspectral imagery and synchronous field spectra

E. Vaudour[a,*], J.M. Gilliot[a], L. Bel[b], J. Lefevre[c], K. Chehdi[c]

[a] UMR ECOSYS, AgroParisTech, INRA, Université Paris-Saclay, 78850 Thiverval-Grignon, France
[b] UMR MIA-Paris, AgroParisTech, INRA, Université Paris-Saclay, 75005 Paris, France
[c] Université de Rennes 1/IETR UMR CNRS 6164, ENSSAT/TSI2M, 6 rue de Kérampont, B.P. 80518, F-22305 Lannion cedex, France

prior to the launching of Sentinel-2

Table 7
Expected error according to measurement method, scale and sensor (Vaudour et al., 2012, 2013; this study).

Scale	Whatever	Field	Field	Region	Region	Region	Region
Method	Dry combustion	Lab NIRS spectroscopy	Vis-NIR airborne image	Lab NIRS spectroscopy	Vis-NIR-SWIR field spectra	Vis-NIR airborne image	Vis-NIR -SWIR multispectral satellite image
Expected error ($g\,kg^{-1}$)	0.4–0.6	0.80–0.95	3	3	4	4–4.5	4.6–5

Vaudour et al., 2016

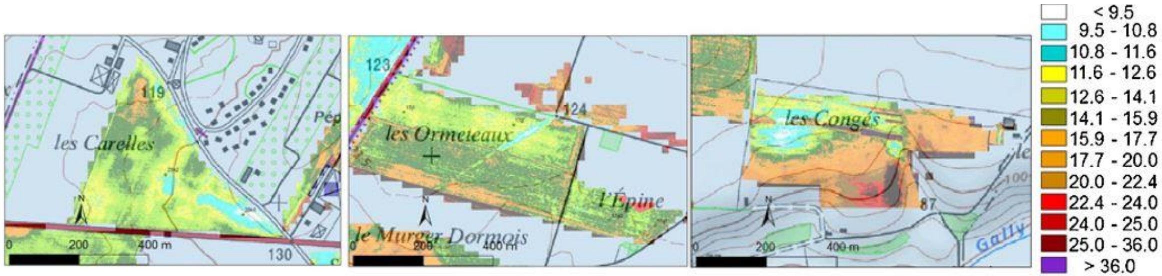


Fig. 10. Within-field variations in SOC predicted contents. In transparency, 1:25,000 topographical map Scan25®, Copyright French Geographical Institute (IGN).

Remote Sensing of Environment 223 (2019) 21–33

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Sentinel-2 image capacities to predict common topsoil properties

Vaudour et al., 2019a

Sentinel-2 image capacities to predict common topsoil properties of temperate and Mediterranean agroecosystems

E. Vaudour[a,*], C. Gomez[b], Y. Fouad[c], P. Lagacherie[b]

[a] UMR ECOSYS, AgroParisTech, INRA, Université Paris-Saclay, 78850, Thiverval-Grignon, France
[b] LISAH, Univ Montpellier, INRA, IRD, Montpellier SupAgro, Montpellier, France
[c] UMR SAS, Agrocampus Ouest, INRA, 35042 Rennes, France

doi.org/10.1016/j.rse.2019.01.006

Temperate soils

haplic luvisols

rendzic, calcaric cambisols

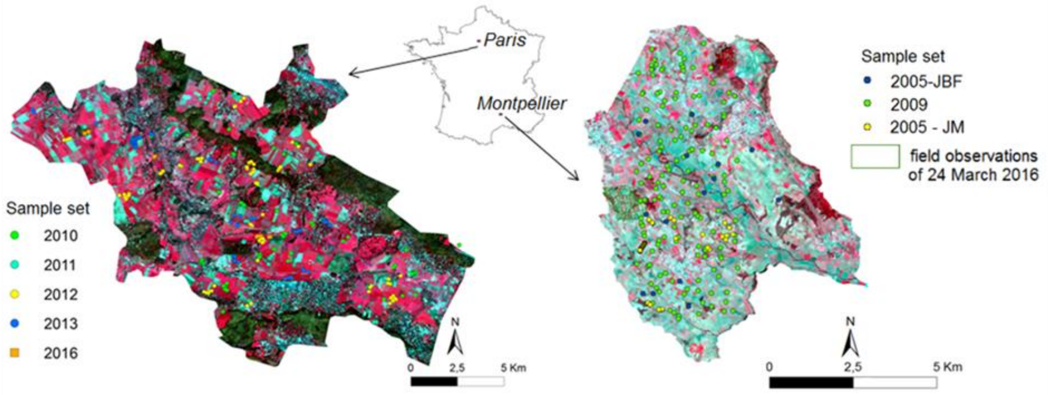
colluvic cambisols

colluvic cambisols (stagnic)

Crahet, 1992

Versailles Plain
Annual crops
221 km²

Lower Peyne valley
vineyards
48 km²



12/03/2016

19/03/2016

Mediterranean soils

colluvic cambisols (arenic)

chromic luvisols

calcaric leptosols

calcisols

Coulouma, 2008

PLSR leave-one-out cross-validation, 10 spectral bands with 10m/20m spatial resolution

Remote Sensing of Environment 223 (2019) 21–33

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Performances of Sentinel-2-derived spectral prediction models

Sentinel-2 image capacities to predict common topsoil properties of temperate and Mediterranean agroecosystems

E. Vaudour[a,*], C. Gomez[b], Y. Fouad[c], P. Lagacherie[b]

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[b] LISAH, Univ Montpellier, INRA, IRD, Montpellier SupAgro, Montpellier, France
[c] UMR SAS, Agrocampus Ouest, INRA, 35042 Rennes, France

doi.org/10.1016/j.rse.2019.01.006

Performance group	**R_{cv}^2**	**RPD_{cv}**	**Soil property Temperate agroecosystem (Versailles)**	**Soil property Mediterranean agroecosystem (Montpellier)**
i) Intermediate to high	≥ 0,5	≥ 1,4	**SOC**, pH, CEC, $CaCO_3$	
ii) near-intermediate	0,4	1,3	clay	clay, Fe, CEC
iii) poor	< 0,4	~1	silt, sand	silt, sand, **SOC**, pH, $CaCO_3$

Vaudour et al., 2019a

Remote Sensing of Environment 223 (2019) 21–33

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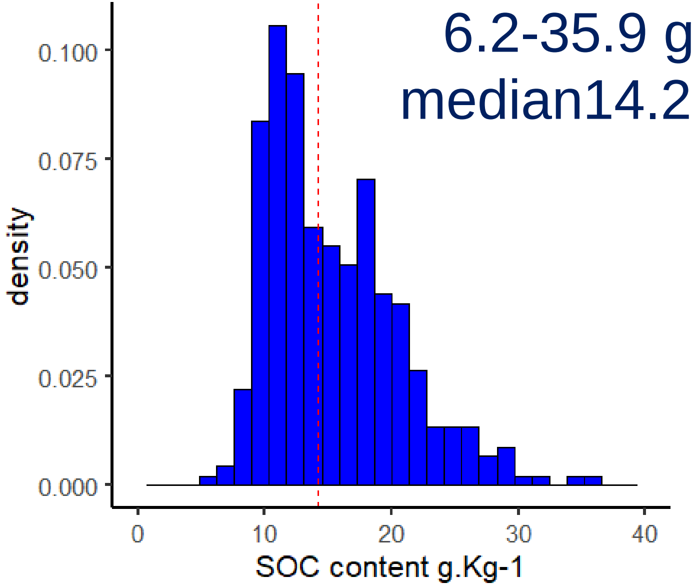
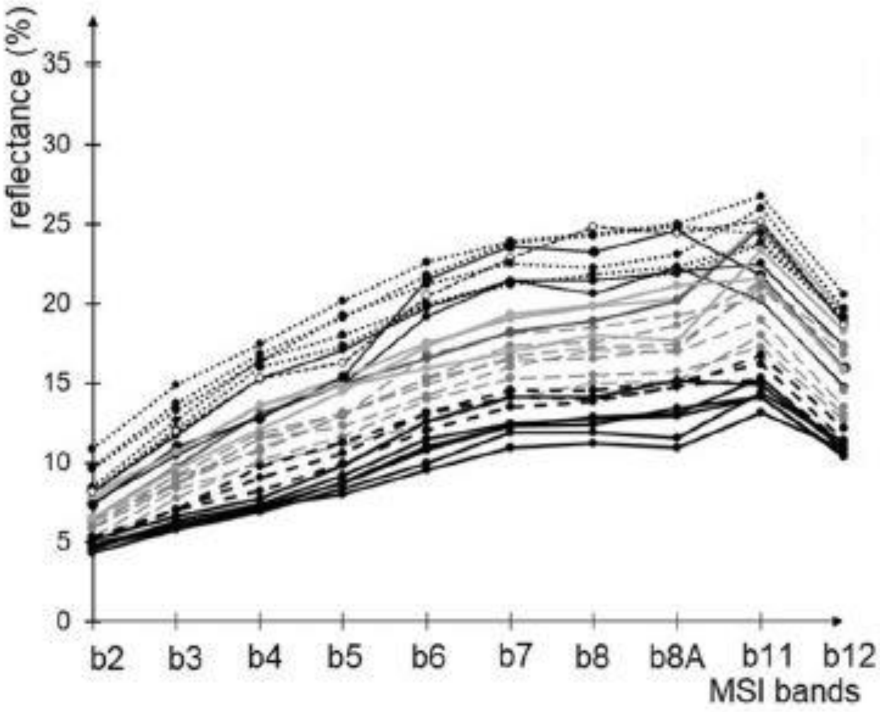
[c] UMR SAS, Agrocampus Ouest, INRA, 35042 Rennes, France

doi.org/10.1016/j.rse.2019.01.006

Sentinel-2 soil spectra

6.2-35.9 $g.Kg^{-1}$
median14.2 $g.Kg^{-1}$





Vaudour et al., 2019a

remote sensing

MDPI

Article

The Impact of Acquisition Date on the Prediction Performance of Topsoil Organic Carbon from Sentinel-2 for Croplands

Emmanuelle Vaudour [1,*], Cécile Gomez [2], Thomas Loiseau [3], Nicolas Baghdadi [4], Benjamin Loubet [1], Dominique Arrouays [3], Leïla Ali [1,2] and Philippe Lagacherie [2]

doi.org/10.3390/rs11182143

Impact of acquisition date

CrossVal PLSR	nb samples	$RMSE_{CV}$ ($g.Kg^{-1}$)	R^2_{CV}	RPD_{CV}	Performance group
12/03/16	83	4.78	0.16	1.1	poor
15/03/16	84	**3.79**	**0.48**	**1.4**	**intermediate**
14/04/16	86	5.05	0.003	1.0	poor
30/11/16	199	5.07	0.02	1.0	poor
27/12/16	173	4.82	0.26	1.2	poor
27/03/17	147	4.45	0.33	1.2	poor
30/03/17	144	4.68	0.29	1.2	poor
09/04/17	125	**3.38**	**0.46**	**1.4**	**intermediate**
19/04/17	122	**3.02**	**0.58**	**1.5**	**intermediate**

Vaudour et al., 2019b

Influence of soil surface roughness

remote sensing MDPI

Article

The Impact of Acquisition Date on the Prediction Performance of Topsoil Organic Carbon from Sentinel-2 for Croplands

Emmanuelle Vaudour [1,*], Cécile Gomez [2], Thomas Loiseau [3], Nicolas Baghdadi [4], Benjamin Loubet [1], Dominique Arrouays [3], Leïla Ali [1,2] and Philippe Lagacherie [2]

doi.org/10.3390/rs11182143

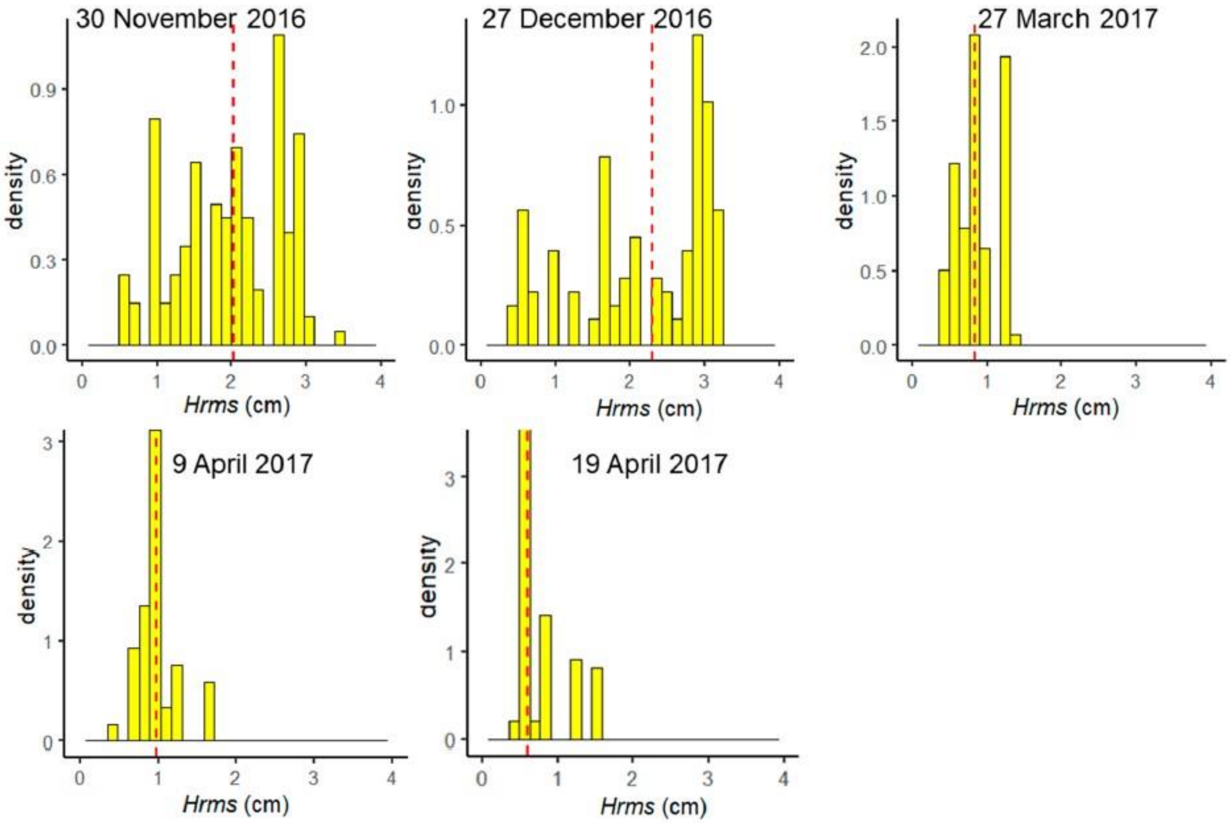
water MDPI

Article

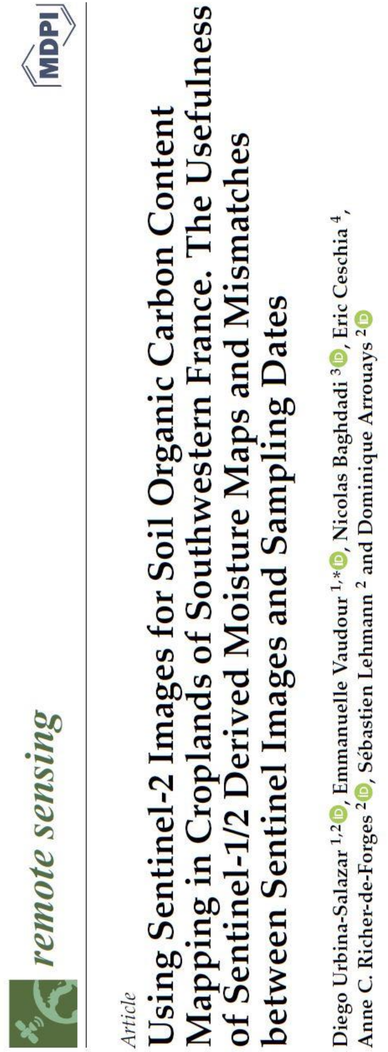
Potential of Sentinel-1 Images for Estimating the Soil Roughness over Bare Agricultural Soils

Nicolas Baghdadi [1,*], Mohammad El Hajj [1], Mohammad Choker [1], Mehrez Zribi [2], Hassan Bazzi [1], Emmanuelle Vaudour [3], Jean-Marc Gilliot [3] and Dav M. Ebengo [3]

doi:10.3390/w10020131



Baghdadi et al., 2018; Vaudour et al., 2019b


remote sensing

MDPI

Article

Using Sentinel-2 Images for Soil Organic Carbon Content Mapping in Croplands of Southwestern France. The Usefulness of Sentinel-1/2 Derived Moisture Maps and Mismatches between Sentinel Images and Sampling Dates

Diego Urbina-Salazar [1,2], Emmanuelle Vaudour [1,*], Nicolas Baghdadi [3], Eric Ceschia [4], Anne C. Richer-de-Forges [2], Sébastien Lehmann [2] and Dominique Arrouays [2]

doi:10.3390/rs13245115

Soilscape units well captured

Urbina-Salazar et al, 2021

- ✓ RMSEcv~6g.kg^{-1}, RPD~1.7-1.8
- ✓ pas d'amélioration avec %vol SMP comme covariable mais facilitation choix dates
- ✓ adéquation avec unités morphologiques (veracrisols)

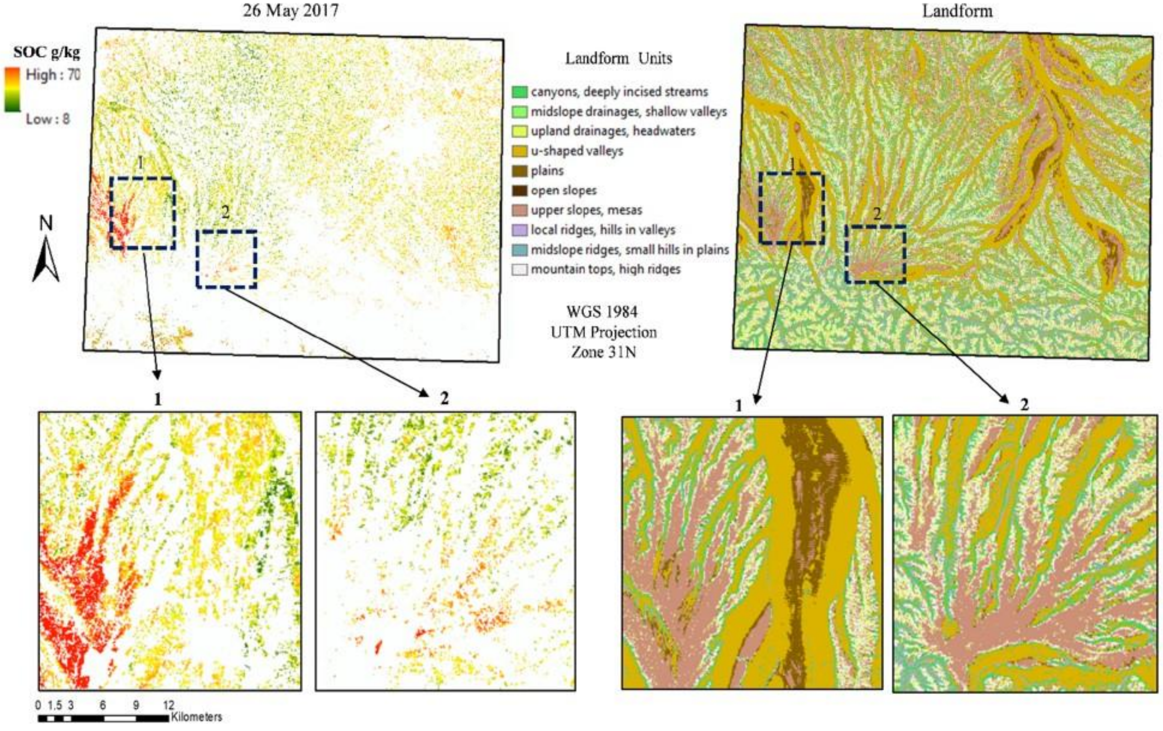
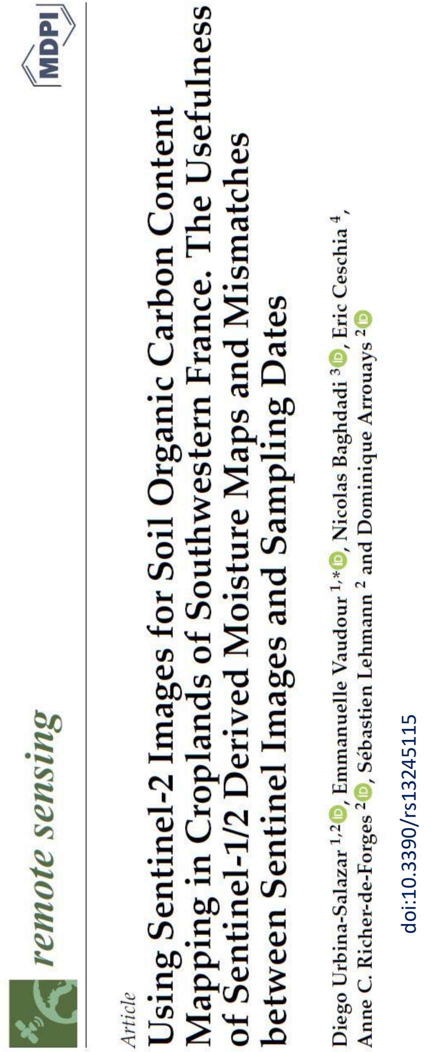


Figure 7. Zooming into the SOC map and the landforms of the study area.



remote sensing

MDPI

Article

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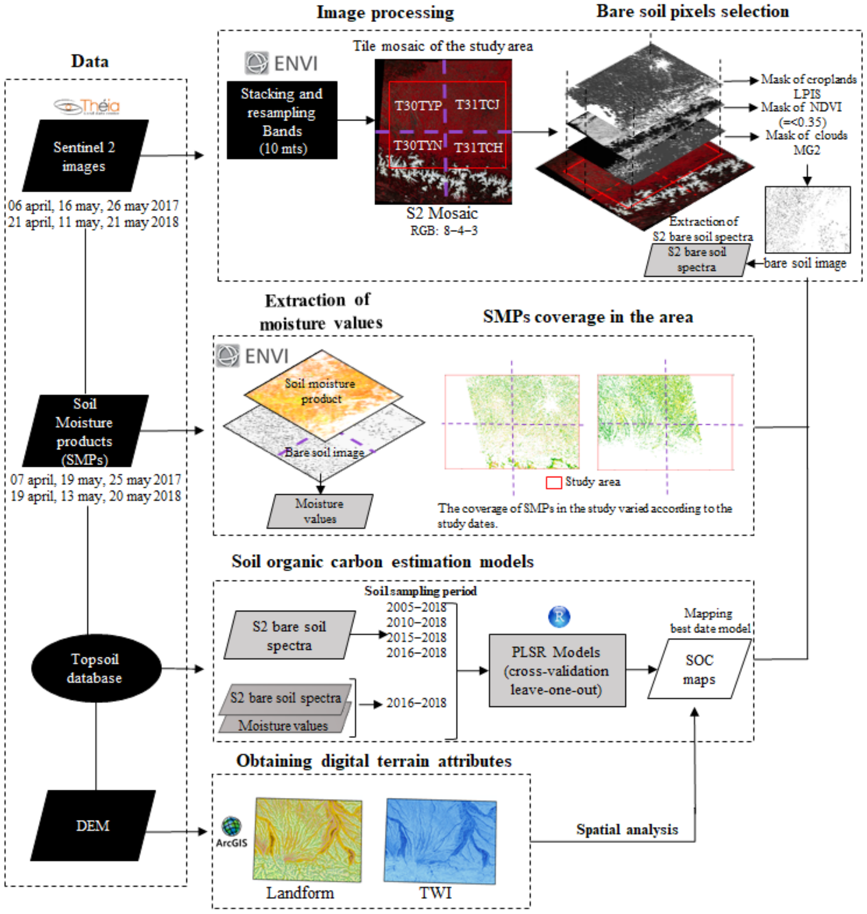


Need to handle several tiles and soil datasets – best results with matching data

- ✓ 4 tiles;
- ✓ varied soil datasets including LUCAS;

Urbina-Salazar et al, 2021

Remote Sensing of Environment 223 (2019) 21–33

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

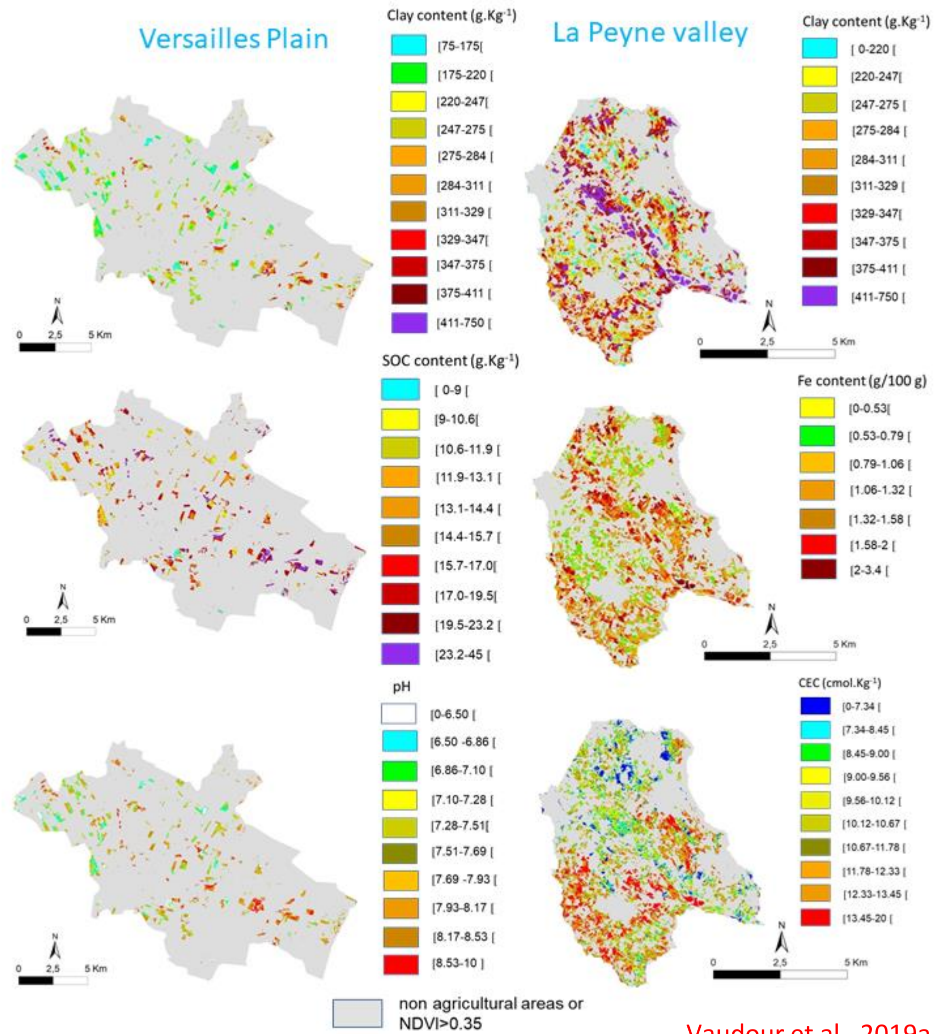
Sentinel-2 image capacities to predict common topsoil properties of temperate and Mediterranean agroecosystems

E. Vaudour[a,*], C. Gomez[b], Y. Fouad[c], P. Lagacherie[b]

[a] UMR ECOSYS, AgroParisTech, INRA, Université Paris-Saclay, 78850, Thiverval-Grignon, France
[b] LISAH, Univ Montpellier, INRA, IRD, Montpellier SupAgro, Montpellier, France
[c] UMR SAS, Agrocampus Ouest, INRA, 35042 Rennes, France

doi.org/10.1016/j.rse.2019.01.006

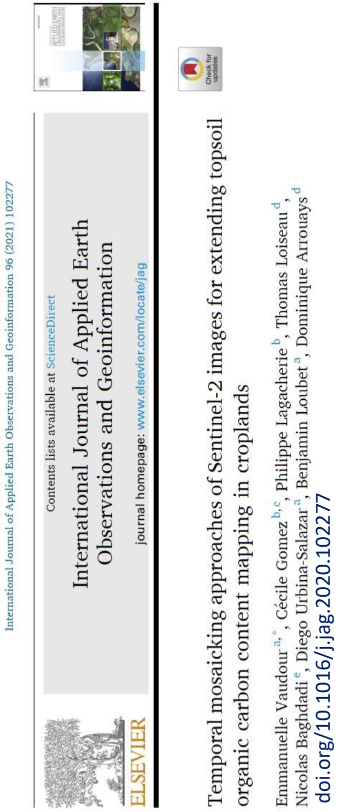
Maps derived from Sentinel-2



Vaudour et al., 2019a

Bare soil extent varies with date

Vaudour et al., 2021


International Journal of Applied Earth Observations and Geoinformation 96 (2021) 102277

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Temporal mosaicking approaches of Sentinel-2 images for extending topsoil organic carbon content mapping in croplands

Emmanuelle Vaudour[a,*], Cécile Gomez[b,c], Philippe Lagacherie[b], Thomas Loiseau[d], Nicolas Baghdadi[e], Diego Urbina-Salazar[a], Benjamin Loubet[a], Dominique Arrouays[d]

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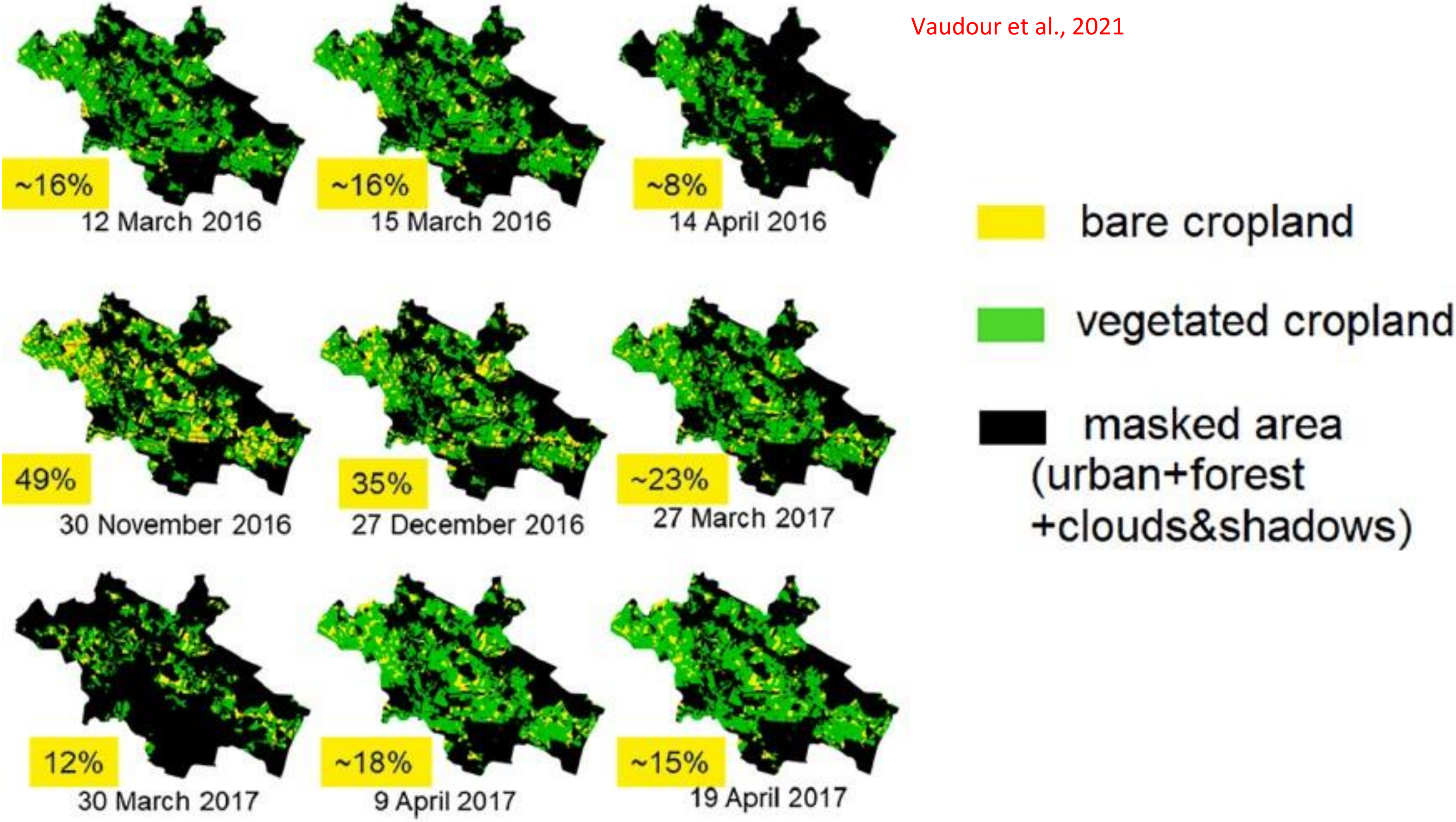
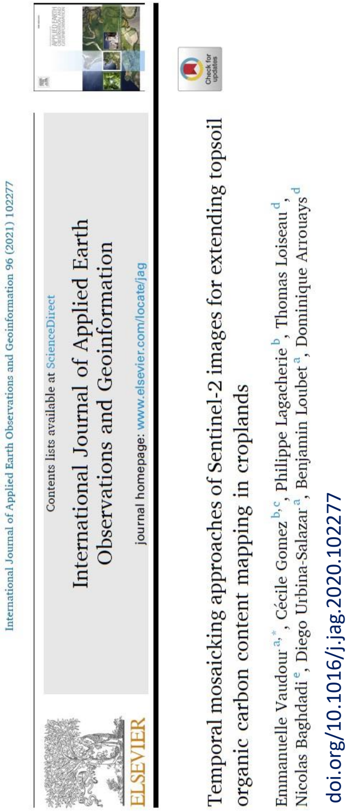


Fig. 4. Map of the percentage of bare soil coverage for the agricultural area according to acquisition date (NDVI ≤ 0.35).

Temporal mosaicking strategies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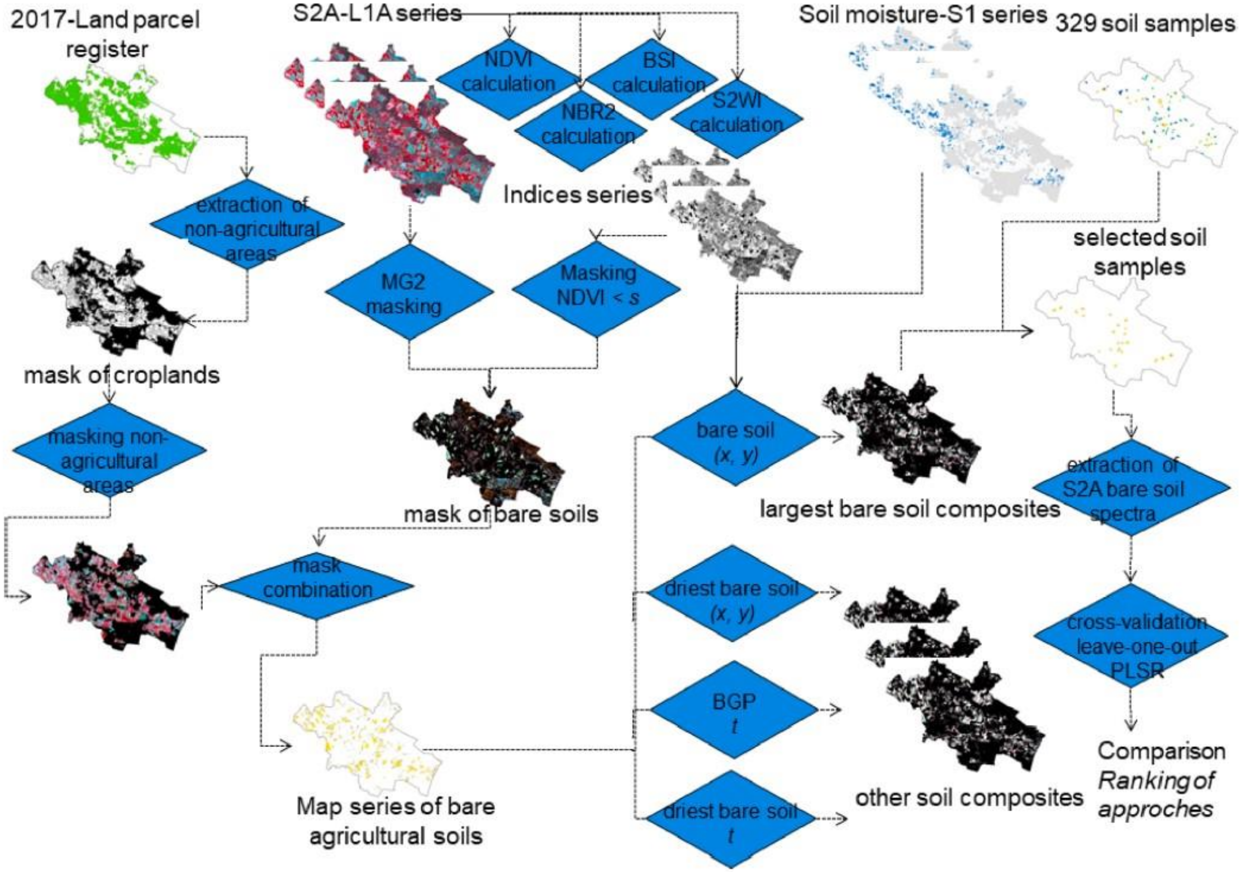
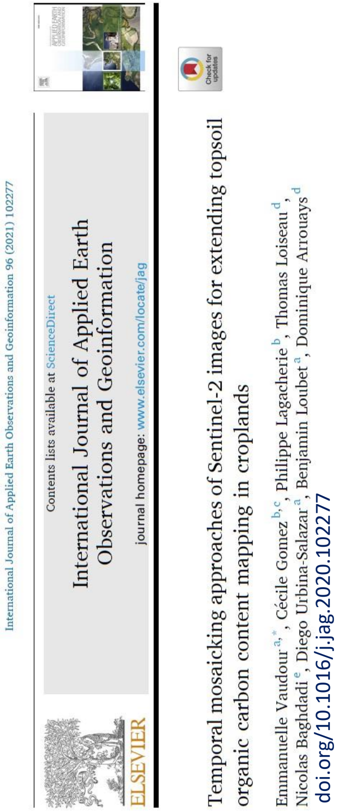


Fig. 3. General flowchart for the mosaicking approach (s = NDVI threshold of either 0.27 or 0.35; BGP = best global performance).

Vaudour et al., 2021

Best strategy relies on mean SM+max areal coverage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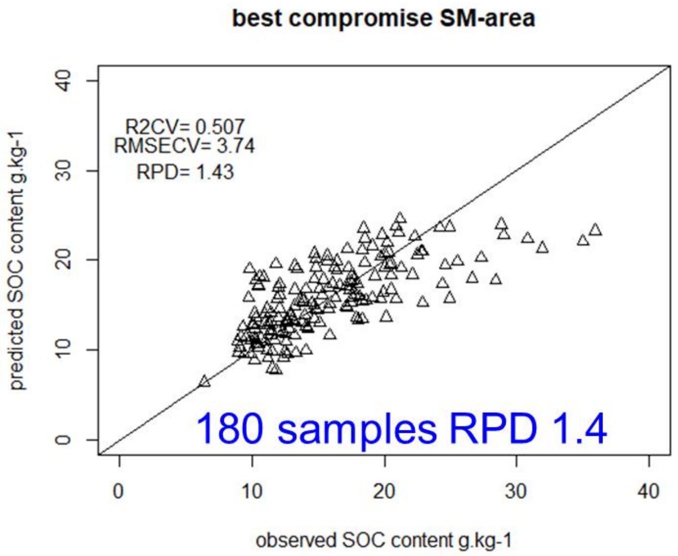
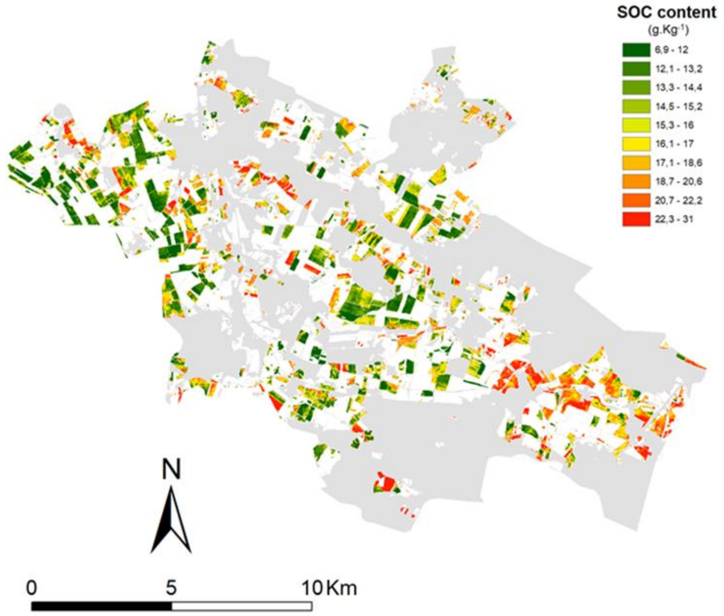
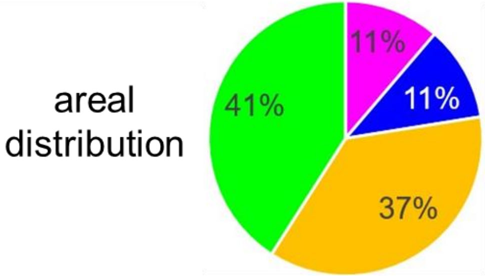
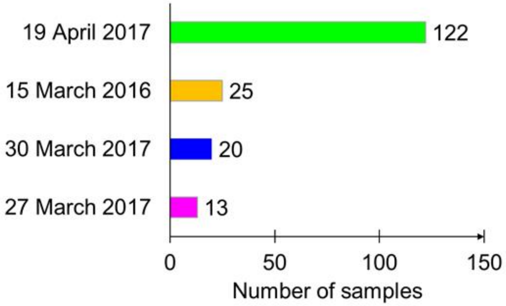






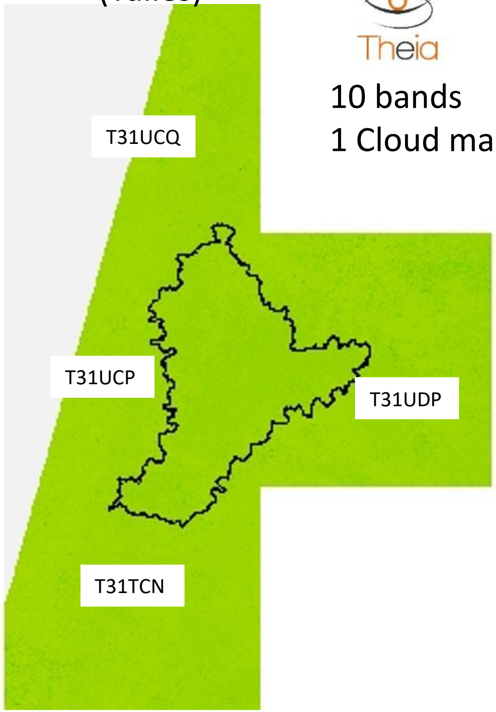


agricultural area predicted *2,44 compared to best single date

Vaudour et al.. 2021

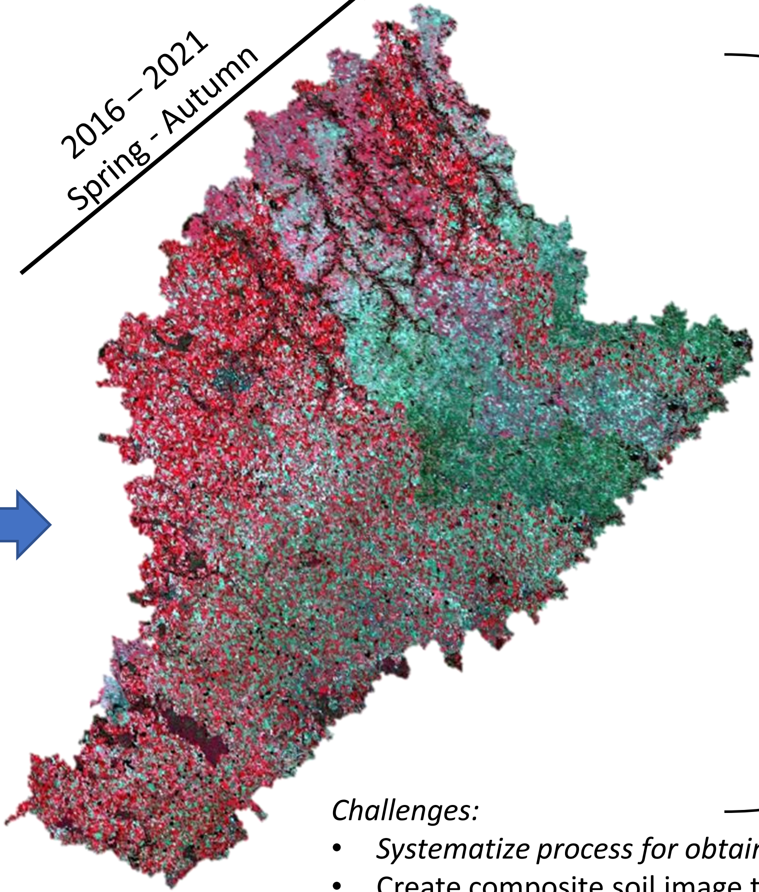
Beauce (in progress)

Area coverage
(Tuiles)



10 bands
1 Cloud mask

2016 – 2021
Spring - Autumn



73 single dates
Approx 500 GB

Challenges:

- *Systematize process for obtaining and processing images*
- Create composite soil image to maximize area and use the sample data available.
- To determine if the use of S2 to predict SOC is useful for this area with different soil, landforms and climatic conditions.

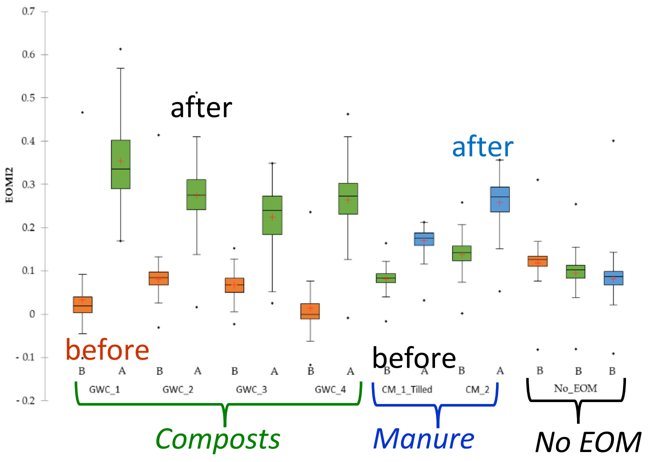
URBINA-SALAZAR, thèse en cours

Maxence Dodin [1,2], Hunter D. Smith [1,2], Florent Levavasseur [1], Dalila Hadjar [1], Sabine Houot [1] and Emmanuelle Vaudour [1,*]

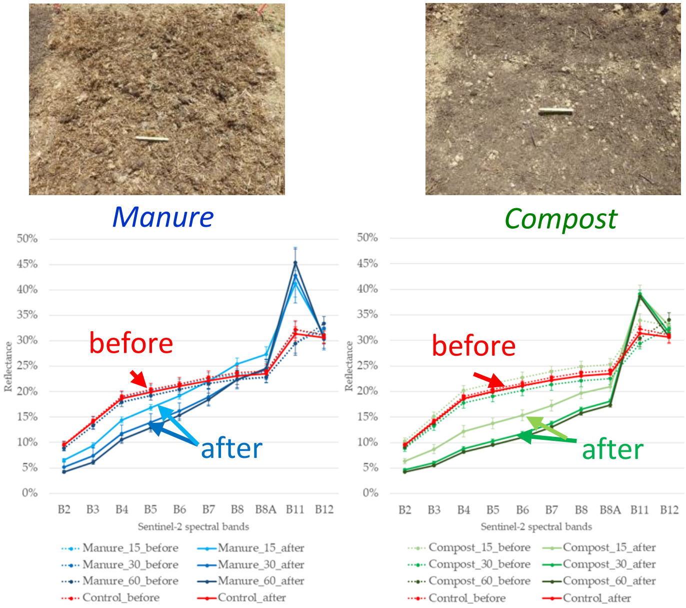
doi :10.3390/rs13091616

S2 spectra detect compost and manure

EOMI2 index from S2-spectra



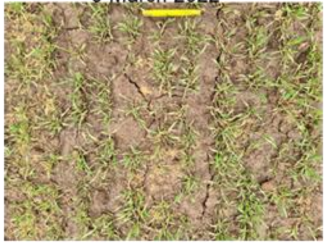
Simulated S2- field spectra



Dodin et al., 2021

Field spectroscopy over INRAE-Nouzilly experiment

9 March 2022

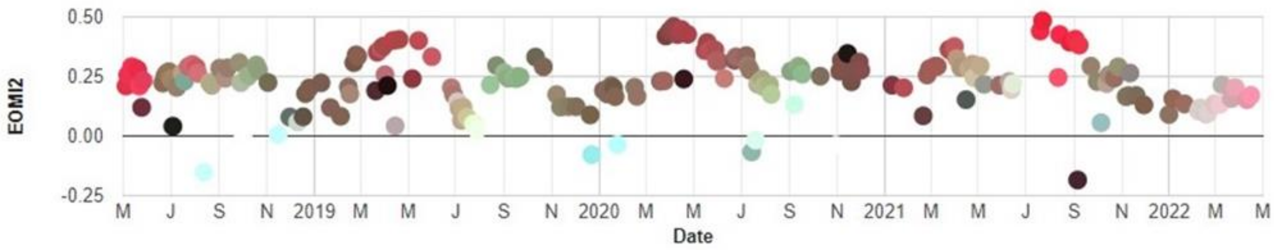


16 March 2022

Digestate derived from methanization – 1 day after spreading

9 March 2022

16 March 2022



DODIN, thèse en cours

Conclusion générale

- résultats encourageants avec Sentinel-2
- extrapolations à divers agroecosystèmes and types de sols ; synergie de plusieurs projets en cours échelons national/européen
- utilisation accrue de données spatio-temporelles
- besoin de développements méthodologiques : projet en construction

Vaudour E., 2017 - https://imaggeo.egu.eu/view/12252